

**HIGH  $p_T$  HADRONS IN AU+AU COLLISIONS AT RHIC**

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High  $p_T$  hadrons produced in ultra-relativistic heavy-ion collisions at RHIC probe nuclear matter at extreme conditions of high energy density. Experimental measurements in Au+Au collisions at  $\sqrt{s_{NN}}=130, 200$  GeV establish the existence of strong medium effects on hadron production well into the perturbative regime.

One of the fundamental predictions of the Quantum Chromodynamics (QCD) is the existence of a deconfined state of quarks and gluons at the energy densities above  $1 \text{ GeV/fm}^3$ <sup>1</sup>. This strongly interacting medium, the Quark Gluon Plasma (QGP), may be created in the laboratory by the collision of heavy nuclei at high energy. The current experimental program at the Relativistic Heavy-Ion Collider (RHIC) is aimed at detecting the new state of matter and studying its properties.

High  $p_T$  hadrons are produced in the initial collisions of incoming partons with large momentum transfer. Hard scattered partons fragment into a high energy cluster (jet) of hadrons. Partons propagating through a dense system may interact with the surrounding medium radiating soft gluons at a rate proportional to the energy density of the medium. The measurements of radiative energy loss (jet quenching) in dense matter may provide a direct probe of the energy density<sup>2</sup>.

The large multiplicities in nuclear collisions make full jet reconstruction impractical. Correlations of high  $p_T$  hadrons in pseudorapidity and azimuth allow the identification of jets on a statistical basis. First hints of jets at RHIC came from the two-particle azimuthal correlations of high  $p_T$  charged hadrons in Au+Au collisions at  $\sqrt{s_{NN}}=130$  GeV<sup>3</sup>. Similar analyses performed for  $\sqrt{s_{NN}}=200$  GeV<sup>4,5</sup> directly show that hadrons at  $p_T > 3 - 4 \text{ GeV/c}$  result from the fragmentation of jets.

Hadrons from jet fragmentation may carry a large fraction of jet momen-

tum (leading hadrons). In the absence of nuclear medium effects, the rate of hard processes should scale with the number of binary nucleon-nucleon collisions. The yield of leading hadrons measured in Au+Au collisions at  $\sqrt{s_{NN}}=130$  GeV has been shown to be significantly suppressed<sup>6,7</sup>, indicating substantial in-medium interactions. The high statistics 200 GeV data extended the measurements of hadron spectra to  $p_T = 12$  GeV/c. Fig.1 shows the suppression of charged hadrons in central Au+Au collisions rel-

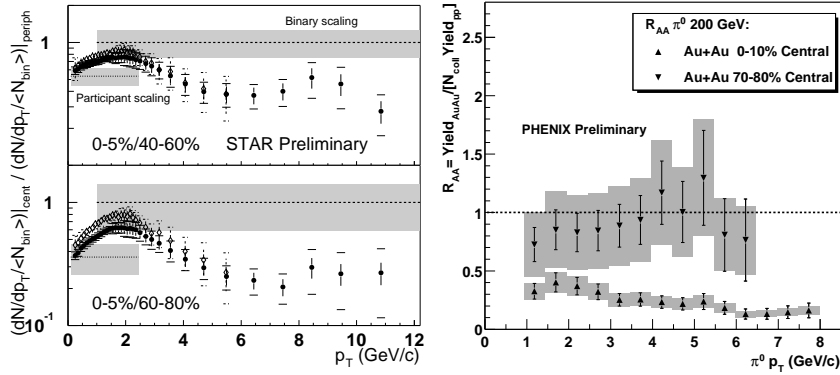


Figure 1. Suppression for charged hadrons (left panel, STAR) and  $\pi^0$  (right panel, PHENIX).

ative to scaled peripheral Au+Au collisions (STAR<sup>8</sup>) and of neutral pions in central Au+Au collisions relative to scaled p+p collisions (PHENIX<sup>9</sup>). Suppression factors of 4-5 are observed for both  $\pi^0$ s and charged hadrons, with weak dependence on  $p_T$  at  $p_T > 5$  GeV/c. The recent pQCD calculations incorporating effects of Cronin enhancement, nuclear shadowing and energy loss may describe the observed suppression<sup>10</sup>, but a disentangling of the effects awaits the upcoming data from d+Au collisions.

The initial spatial almond-shaped geometry of the reaction zone in non-central nuclear collisions can be used to study the propagation of partons and/or their fragmentation products through the azimuthally asymmetric system. The azimuthal anisotropy of final state hadrons in non-central collisions is quantified by the coefficients of the Fourier decomposition of the azimuthal particle distributions, with the second harmonic coefficient  $v_2$  referred to as elliptic flow. The elliptic flow measurements for  $p_T < 2$  GeV/c agree in detail with hydrodynamic calculations<sup>11</sup>. Fig.2 (left panel)

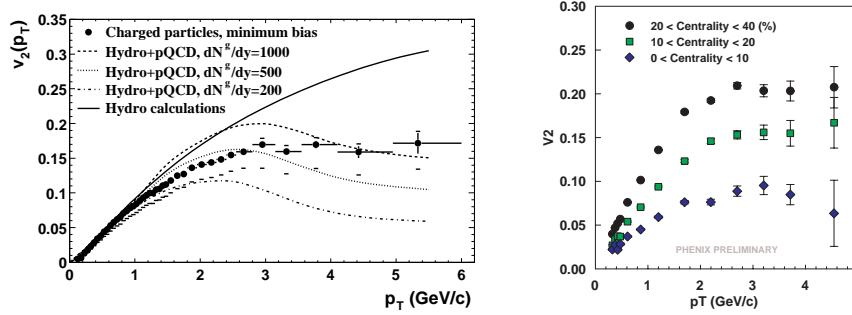


Figure 2. Elliptic flow  $v_2(p_T)$  for charged hadrons. Left panel: minimum bias at 130 GeV (STAR) compared to hydro and pQCD calculation. Right panel: centrality dependence at 200 GeV (PHENIX).

shows the elliptic flow  $v_2$  as a function of  $p_T$  for Au+Au collisions at 130 GeV<sup>3</sup>. Elliptic flow rises almost linearly with transverse momentum up to 2 GeV/c, behavior that is well described by hydrodynamic calculation. Above  $p_T \sim 2$  GeV/c,  $v_2(p_T)$  deviates from a linear rise and saturates for  $p_T > 3$  GeV/c. The azimuthal anisotropies measured at  $p_T = 4 - 6$  GeV/c are in qualitative agreement with the pQCD calculations including energy loss<sup>12</sup>. Fig.2 (right panel) shows the centrality dependence of  $v_2(p_T)$  measured at 200 GeV by the PHENIX Collaboration<sup>13</sup>. Finite values of  $v_2$  persist to  $p_T = 4.5$  GeV/c for all centralities. The results from the STAR Collaboration show the finite values of  $v_2$  up to  $p_T < 10$  GeV/c for non-central collisions<sup>14</sup>. However, at present the measured values of  $v_2$  contain a non-flow component which at high  $p_T$  comes from intra-jet correlations. A quantitative understanding of this effect at the highest  $p_T$  is still needed.

Additional striking evidence of in-medium effects on high  $p_T$  particle production comes from the analysis of back-to-back jet correlations by the STAR Collaboration<sup>4,15</sup>. Fig.3 shows the azimuthal angular distribution between pairs of high  $p_T$  hadrons for the peripheral and most central Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. The strength of near-side correlations for both centralities is consistent with that measured in p+p collisions. The away-side (back-to-back) correlations in peripheral Au+Au collisions may be described by an incoherent superposition of jet-like correlations measured in p+p and elliptic flow. However, back-to-back jet production is strongly suppressed in the most central Au+Au collisions. This indicates a substantial interaction as the hard-scattered partons or their fragmentation

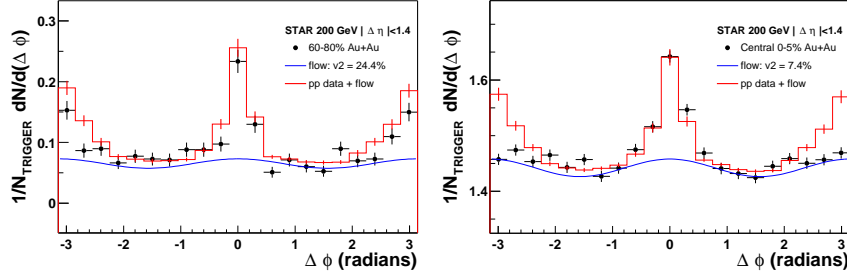


Figure 3. Azimuthal correlations of high  $p_T$  hadron pairs in Au+Au compared to p+p plus elliptic flow (STAR). Left panel: peripheral collisions. Right panel: central collisions.

products traverse the medium.

Up to now, the high  $p_T$  data from RHIC have provided a lot of exciting results. What is missing, however, is a coherent theoretical description of the experimental data. Many different approaches are taken in attempt to describe the data, such as the pQCD with energy loss, gluon saturation, parton cascade, surface emission, etc. The upcoming d+Au run at RHIC will shed light on the magnitude of initial state effects and will help to rule out certain theoretical scenarios.

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